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## Stars Outside the Hipparcos List Closely Encountering the Solar System

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**Abstract**—Based on currently available kinematic data, we have searched for stars outside the Hipparcos list that either closely encountered in the past or will encounter in the future the Solar system within several parsecs. For the first time, we have identified two single stars, GJ 3379 (G 099–049) and GJ 3323 (LHS 1723), as candidate for a close encounter with the solar orbit. The star GJ 3379 could encounter the Sun more closely to a minimum distance  $d_{min} = 1.32 \pm 0.03$  pc at time  $t_{min} = -163 \pm 3$  thousand years. We have found two potential candidates for a close encounter that have only photometrical distances: the white dwarf SSSPM J1549–3544 without any data on its radial velocity and the L-dwarf SDSS J1416+1348. The probabilities of their penetration into the Oort cloud region are 0.09 (at a model radial velocity  $|V_r| = 50$  km s<sup>−1</sup>) and 0.05, respectively.

## 1 INTRODUCTION

The Oort comet cloud (Oort 1950) is presumed to be located at the outer boundaries of the Solar system. It is highly likely that the cloud has a spherical shape and a radius of about  $1 \times 10^5$  AU (0.485 pc). Close encounters of Galactic field stars with the Solar system play an important role in the dynamical evolution of the Oort cloud. In particular, such passages of stars can provoke the formation of comet showers that reach the region of the giant planets (Emel’yanenko et al. 2007; Leto et al. 2008; Rickman et al. 2008). Several researchers associate the traces of comet bombardments of the Earth with the impact of such showers (Wickramasinghe and Napier 2008).

The question about the encounters of stars with the Sun within distances  $r < 2 - 5$  pc was considered by Matthews (1997) and Mülläri and Orlov (1996) using various ground-based observations and by Garcia-Sanchez et al. (1999; 2001), Dybczyński (2006) and Bobylev (2010) based on Hipparcos (1997) data in combination with stellar radial velocities. About 160 Hipparcos stars are known from the solar neighborhood 50 pc in radius that either encountered or will encounter the Solar system within  $r < 5$  pc in a time interval of  $\pm 10$  Myr.

The goal of this study is to search for candidate stars closely encountering the Sun based on currently available kinematic data on stars that do not belong to the Hipparcos catalogue. Indeed, since the paper by Mülläri and Orlov (1996), who analyzed all stars from the catalog by Gliese and Jahreiß (1991), new observational data have appeared. In this paper, we solve the problem of statistical simulations by taking into account the

random errors in the input data in order to estimate the probability of a star penetrating into the Oort cloud region.

## 2 THE METHODS

### 2.1 Orbit construction

We use a rectangular Galactic coordinate system with the axes directed away from the observer toward the Galaxy center ( $l=0^\circ$ ,  $b=0^\circ$ , the  $X$  axis), in the direction of Galactic rotation ( $l=90^\circ$ ,  $b=0^\circ$ , the  $Y$  axis), and toward the North Pole ( $b=90^\circ$ , the  $Z$  axis). The corresponding space velocity components of an object  $U, V, W$  are also directed along the  $X, Y, Z$  axes. The epicyclic approximation (Lindblad, 1927) allows the stellar orbits to be constructed in a coordinate system rotating around the Galactic center. The equations are (Fuchs et al., 2006)

$$\begin{aligned} X(t) &= X(0) + \frac{U(0)}{\kappa} \sin(\kappa t) + \frac{V(0)}{2B} (1 - \cos(\kappa t)), \\ Y(t) &= Y(0) + 2A \left( X(0) + \frac{V(0)}{2B} \right) t - \frac{\Omega_0}{B\kappa} V(0) \sin(\kappa t) + \frac{2\Omega_0}{\kappa^2} U(0) (1 - \cos(\kappa t)), \\ Z(t) &= \frac{W(0)}{\nu} \sin(\nu t) + Z(0) \cos(\nu t), \end{aligned} \quad (1)$$

where  $t$  is the time in Myr (we proceed from the ratio  $\text{pc}/\text{Myr} = 0.978 \text{ km s}^{-1}$ );  $A$  and  $B$  are the Oort constants;  $\kappa = \sqrt{-4\Omega_0 B}$  is the epicyclic frequency;  $\Omega_0$  is the angular velocity of Galactic rotation for the local standard of rest,  $\Omega_0 = A - B$ ;  $\nu = \sqrt{4\pi G \rho_0}$  is the vertical oscillation frequency, where  $G$  is the gravitational constant and  $\rho_0$  is the star density in the solar neighborhood.

The parameters  $X(0), Y(0), Z(0)$  and  $U(0), V(0), W(0)$  in the system of equations (1) denote the current stellar positions and velocities. The displacement of the Sun from the Galactic plane is taken to be  $Z(0) = 17 \text{ pc}$  (Joshi, 2007). We calculate the velocities  $U, V, W$  relative to the local standard of rest (LSR) with  $(U, V, W)_{\text{LSR}} = (10.00, 5.25, 7.17) \text{ km s}^{-1}$  (Dehnen and Binney, 1998).

At present, the question about the specific values of the Sun's peculiar velocity relative to the local standard of rest  $(U, V, W)_{\text{LSR}}$  is being actively debated (Francis and Anderson, 2009; Binney, 2010). Arguments for increasing the velocity  $V_{\text{LSR}}$  from  $5 \text{ km s}^{-1}$  to  $\approx 11 \text{ km s}^{-1}$  are adduced. Since, in our case, both the solar orbit and the stellar orbit are constructed with these values, the influence of the adopted  $V_{\text{LSR}}$  is virtually imperceptible. This is confirmed by good agreement between the encounter parameters of, for example, the star GJ 710 and other stars obtained with various values of  $(U, V, W)_{\text{LSR}}$  by Bobylev (2010) and Garcia-Sanchez et al. (2001).

We took  $\rho_0 = 0.1 M_\odot/\text{pc}^3$  (Holmberg and Flinn, 2004), which gives  $\nu = 74 \text{ km s}^{-1} \text{ kpc}^{-1}$ . We used the following Oort constants found by Bobylev et al. (2008):  $A = 15.5 \pm 0.3 \text{ km s}^{-1} \text{ kpc}^{-1}$  and  $B = -12.2 \pm 0.7 \text{ km s}^{-1} \text{ kpc}^{-1}$ ;  $\kappa = 37 \text{ km s}^{-1} \text{ kpc}^{-1}$  corresponds to these values.

Note that we neglect the gravitational interaction between the star and the Sun.

## 2.2 Statistical Simulations

In accordance with the method of Monte Carlo statistical simulations, we compute a set of orbits for each object by taking into account the random errors in the input data. For each star, we compute the encounter parameter between the stellar and solar orbits,  $d = \sqrt{\Delta X^2(t) + \Delta Y^2(t) + \Delta Z^2(t)}$ . We characterize the time of the closest encounter by two numbers,  $d_{min}$  and  $t_{min}$ . The errors in the stellar parameters are assumed to be distributed normally with a dispersion  $\sigma$ . The errors are added to the equatorial coordinates, proper motion components, parallax, and radial velocity of the star. We separately consider stars with spectroscopic distance estimates obtained with typical errors of 20–30%. In this case, the random errors are added to the distance during the simulations.

# 3 RESULTS AND DISCUSSION

## 3.1 Stars with Trigonometric Parallaxes

First, let us consider the solar neighborhood about 10 pc in radius using the list of 100 nearest stars from the Chilean RECONS site (<http://www.chara.gsu.edu/RECONS/>). This list reflects the results published before January 1, 2009. The trigonometric parallax of each star in the list was calculated as a weighted mean of the results of several (from one to four) observations. We are interested in ten RECONS stars that are not Hipparcos ones (see Table 1). Other RECONS stars are ten M dwarfs without any radial velocity estimates and the remaining stars are Hipparcos ones.

The equatorial coordinates and proper motions of the stars in Table 1 were taken from Salim and Gould (2003) and Lépine and Shara (2005), where the proper motions were calculated by comparing the 2MASS stellar positions with those from the Palomar Observatory Sky Survey.

We took the radial velocities from the works of various authors. Note that, according to the original first-class measurements by Nidever et al. (2002), two stars, GL 406 and GL 905, exhibit a high stability in an observing time interval of 1–2 yr. The internal measurement error is  $\pm 0.1 \text{ km s}^{-1}$ ; therefore, they were suggested as candidates for standards to determine the radial velocities. Since these stars are M type dwarfs, the external error in  $V_r$  is  $\pm 0.4 \text{ km s}^{-1}$ . We took the radial velocity of the center of mass for the triple system GL 866 ABC from the plot in Delfosse et al. (1999). Note that, on the whole, the radial velocities for the stars listed in the table differ insignificantly from those in the catalog by Gliese and Jahreiß (1991). Only the star GJ 473, for which the discrepancy in  $V_r$  is two orders of magnitude, constitutes an exception. We will discuss this situation below.

For each star, we constructed its orbit relative to the Sun in the time interval from  $-2 \text{ Myr}$  to  $+2 \text{ Myr}$ . Data on six stars with an encounter parameter  $d < 3 \text{ pc}$  are presented in Table 2 and the trajectories of these stars are shown in Fig.1.

(1) The parameters of the GL 905 encounter with the solar orbit found here are in good agreement with the estimates by Mülläri and Orlov (1996),  $d_{min} = 0.95 \pm 0.11$  pc and  $t_{min} = 36.3 \pm 1.4$  thousand years; our values have considerably smaller random errors due to the currently available data being very accurate.

Note that the encounter parameter for Proxima Cen is  $d_{min} = 0.89 \pm 0.02$  pc (Bobylev, 2010) or  $d_{min} = 0.95 \pm 0.04$  pc (Garcia-Sanchez et al., 2001), which was obtained with a slightly different radial velocity. As we see from Fig.1, GL 905 has a chance to be even slightly closer to the Sun than Proxima Cen in  $\approx 37$  thousand years. At present, we know only two stars with a smaller (than that of GL 905) encounter parameter: GJ 710=HIP 89825 with  $d_{min} = 0.31 \pm 0.17$  pc (Bobylev, 2010) and HIP 85661 with  $d_{min} = 0.94 \pm 0.71$  pc (Garcia-Sanchez et al., 2001).

(2) We have identified the stars GJ 3379 (G 099-049) and GJ 3323 (LHS 1723) as candidates for a close encounter with the solar orbit for the first time. Their trigonometric parallaxes with a relative error  $e_\pi/\pi < 1\%$  were first determined only recently by Henry et al. (2006). Their radial velocities obtained by analyzing the published data from Montes et al. (2001) are also accurate.

(3) As our statistical simulations show, for all six stars from Table 2, the probability of their penetration into the Oort cloud region is essentially zero.

### 3.2 Stars with Indirect Distance Estimates

We do not set the objective to survey all stars with spectrophotometric distance estimates. Note only two interesting stars, SSSPM J1549-3544 and SDSS J1416+1348, which we have been able to reveal using data from Scholz et al. (2004) and Schmidt et al. (2010a; 2010b).

(1) According to Scholz et al. (2004), the kinematic data for SSSPM J1549-3544 are:  $\alpha = 15^h 48^m 40^s.23$ ,  $\delta = -35^\circ 44' 25''.4$ ,  $\mu_\alpha \cos \delta = -591 \pm 8$  mas yr<sup>-1</sup>,  $\mu_\delta = -538 \pm 5$  mas yr<sup>-1</sup>, and  $d_{spec} = 3-4$  pc with an error of 1 pc. This star may be the single cool white dwarf closest to the Sun (closer than the well-known Van Maanen star,  $d = 4.3$  pc). Scholz et al. (2004) obtained the distance  $d_{spec} = 4 \pm 1$  pc using 2MASS photometry and  $d_{spec} = 3 \pm 1$  pc using less accurate SSS (SuperCOSMOS Sky Survey) photometry. Since there are no radial velocity data, the space velocities ( $U, V, W$ ) of this star were estimated by Scholz et al. (2004) for three model radial velocities, -50, 0, and 50 km s<sup>-1</sup>.

Following Scholz et al. (2004), we will use  $d = 4 \pm 1$  pc ( $e_d/d = 25\%$ ) and various model radial velocities for this star. Several trajectories are shown in Fig. 2. As we see from the figure, the sign of the radial velocity determines whether the star could encounter the Sun in the past (positive sign) or in the future (negative sign). We clearly see that the encounter with the Sun becomes increasingly close with increasing magnitude of the radial velocity. Because of the distance estimation error  $\pm 1$  pc, formally there is a chance of very close encounters. For example, when the plot is shifted vertically downward by  $\approx 1$  pc, the stellar trajectories highlighted by the heavy lines fall at the boundary of the Oort cloud.

Table 3 gives two results obtained at fixed radial velocities of the star with the addition of random errors to the proper motion components and the distance  $d$ . We constructed

10 000 model orbits for each case and in  $\approx 900$  cases the star falls into the Oort cloud region,  $d_{min} \leq 0.485$  pc, then  $P_1 = 900/10000$ .

(2) According to Schmidt et al. (2010a, 2010b), the kinematic data for SDSS J1416+1348 are:  $\alpha = 14^h 16^m 24^s.08$ ,  $\delta = 13^\circ 48' 26''.7$ ,  $\mu_\alpha \cos \delta = 88.0 \pm 2.8$  mas yr $^{-1}$ ,  $\mu_\delta = 139.9 \pm 1.3$  mas yr $^{-1}$ , and  $V_r = -42.2 \pm 5.1$  km s $^{-1}$ . The most reliable distance estimate,  $d = 8.0 \pm 1.6$  pc ( $e_d/d = 20\%$ ), was derived by Schmidt et al. (2010a) as a mean of five photometric and spectroscopic determinations from 2MASS infrared data and SDSS optical data.

(3) Our statistical simulations show that both SSSPM J1549–3544 and SDSS J1416+1348 have a nonzero probability of penetrating into the Oort cloud region:  $P_1 = 0.09$  and  $P_1 = 0.05$ , respectively (the last column of Table 3). Both stars are of great interest in the problem being solved.

We may conclude that determining the trigonometric parallaxes and radial velocities of these stars is topical.

(4) Let us now turn to the list of 25 stars from the catalog by Gliese and Jahreiß (1991) that were revealed by Mülläri and Orlov (1996) as candidates for a close encounter with the Solar system. Since 16 of them are Hipparcos stars, the results of the analysis of their trajectories are presented in Garcia-Sanchez et al. (2001) and Bobylev (2010).

Three stars are located within  $d < 10$  pc; these are GJ 905, GJ 473, and GJ 3166. Since the remaining six stars are farther than 10 pc, they were not included in the RECONS list. We have already discussed the encounter parameters of GJ 905 in the previous section.

The star GJ 3166 (designated as No 456 NN in Mülläri and Orlov, 1996) is of great interest, because, according to the estimate by Mülläri and Orlov (1996), it can encounter the Sun to a record distance  $d_{min} = 0.16$  pc at time  $t_{min} = 1600$  thousand years. However, as it turned, there is no information about its proper motion in the catalog by Gliese and Jahreiß(1991). Therefore, its space velocities  $U, V, W$  were calculated by assuming the tangential velocity to be zero,  $V_t = 0$ .

Taking  $d = 20.8$  pc (photometric distance),  $\mu_t = 0$  mas yr $^{-1}$ , and  $V_r = -12$  km s $^{-1}$  for GJ 3166, as in the catalog by Gliese and Jahreiß(1991), we find the encounter parameters  $d_{min} = 0.18$  pc and  $t_{min} = 1708$  thousand years, which confirm the result by Mülläri and Orlov. For the same distance and radial velocity but taking the proper motion components  $\mu_\alpha \cos \delta = -103.3 \pm 8.1$  mas yr $^{-1}$  and  $\mu_\delta = -67.7 \pm 9.2$  mas yr $^{-1}$  from the UCAC3 catalog (Zacharias et al., 2009), we find completely different encounter parameters,  $d_{min} = 15$  pc and  $t_{min} = 590$  thousand years, which are already less interesting in our problem. Note that the absolute proper motions of this star are also available in the XPM catalog (Fedorov et al., 2009):  $\mu_\alpha \cos \delta = -87.2$  mas yr $^{-1}$  and  $\mu_\delta = -68.1$  mas yr $^{-1}$ . These were determined by comparing the 2MASS and Palomar Observatory Sky Survey positions referenced to galaxies with a mean error of about 6 mas yr $^{-1}$  in each coordinate (Bobylev et al., 2010).

Finally, according to the estimate by Mülläri and Orlov (1996), GJ 473 can encounter the Sun very closely,  $d_{min} = 0.29$  pc, at time  $t_{min} = 7.5$  thousand years. These parameters were obtained using the radial velocity  $V_r = -553.7$  km s $^{-1}$  (Gliese and Jahreiß, 1991). GJ 473 (LHS 333=FL Vir=Wolf 424 AB) is a close binary system with a known orbit

(Torres et al., 1999). The measurements by Tinney and Reid (1998) performed with a high-resolution spectrometer yield the system’s heliocentric radial velocity  $V_r = 0.9 \pm 1.7$  km s<sup>-1</sup>. Note that previous measurements also gave a low radial velocity for this system:  $V_r = -5 \pm 5$  km s<sup>-1</sup> (GCRV, Wilson 1953). The radial velocity in the compilation by Gliese and Jahreiß(1991) is probably erroneous. Since the encounter parameters of GJ 473 calculated with its new radial velocity  $V_r = 0.9 \pm 1.7$  km s<sup>-1</sup>,  $d_{min} = 6 \pm 5$  pc and  $t_{min} = -3 \pm 6$  thousand years, are no longer the close encounter parameters, this star was not included in Table 2.

## 4 CONCLUSIONS

Based on currently available kinematic data, we searched for stars that either encountered or will encounter the solar neighborhood within less than 3 pc. We considered stars outside the Hipparcos list. For each of them, there is an estimate of its trigonometric parallax with a relative error  $e_\pi/\pi < 2\%$ , radial velocity, and proper motion components. We found six such stars that are an important supplement to the list of Hipparcos stars closely encountering the Solar system (Garcia-Sanchez et al., 2001; Bobylev, 2001).

For the first time, two single stars, GJ 3379 (G 099-049) and GJ 3323 (LHS 1723), have been identified as candidates for a close encounter with the solar orbit.

We confirmed the remarkable result by Mülläri and Orlov (1996) that the star GL 905 could encounter the Sun fairly closely:  $d_{min} = 0.93 \pm 0.01$  pc and  $t_{min} = 37.1 \pm 0.2$  thousand years.

Two unique stars are located in the immediate solar neighborhood ( $d < 10$  pc)—the white dwarf SSSPM J1549-3544 and the L dwarf SDSS J1416+1348. Our statistical simulations showed that both of them have a nonzero probability of penetrating into the Oort cloud region:  $P_1 = 0.09$  and  $P_1 = 0.05$ , respectively. Determining the trigonometric parallaxes and radial velocities for these stars is topical. This task can be accomplished using both ground-based and space (e.g., GAIA) observations.

Based on new data, we showed that the stars GJ 473 and GJ 3166 are not suitable candidates for a very close encounter with the Solar system as was presumed previously.

## ACKNOWLEDGMENTS

I am grateful to A.T. Bajkova for the software package for statistical simulations. The SIMBAD database and the RECONS site were very helpful in the work. This work was supported by the Russian Foundation for Basic Research (project nos. 08-02-00400 and 09-02-90443-Ukr\_f) and in part by the “Origin and Evolution of Stars and Galaxies” Program of the Presidium of the Russian Academy of Sciences.

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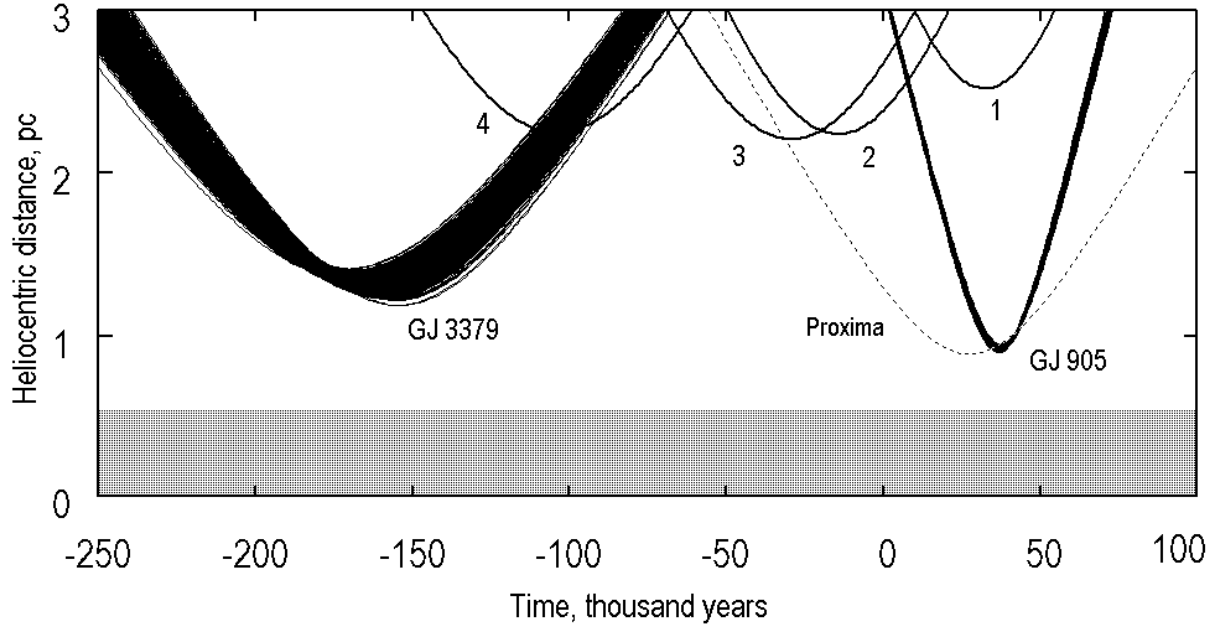


Fig. 1. Trajectories of the stars relative to the Sun: (1) GJ 866, (2) GJ 406, (3) GJ 65, (4) GJ 3323; for GJ 905 and GJ 3379, we give the model trajectories computed by taking into account the random errors in the observational data (1000 realizations). The trajectories hatch the  $3\sigma$  confidence regions, the Oort cloud region is shaded, the dotted line indicates the trajectory of Proxima Cen.



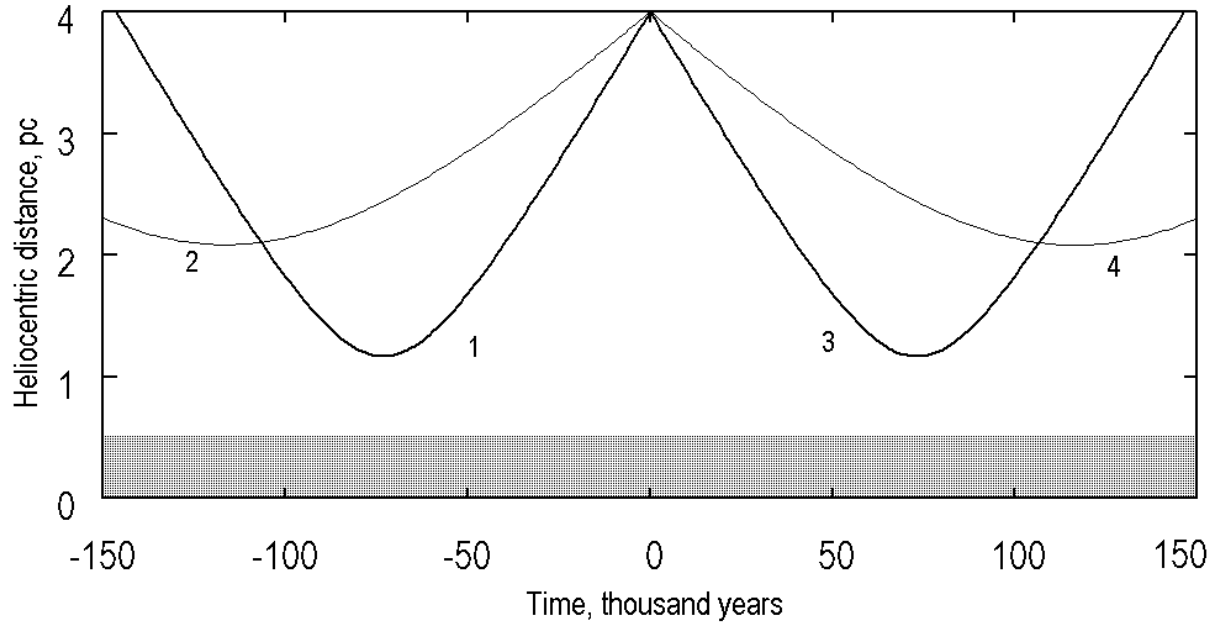


Fig. 2. Model trajectories of the star SSSPM J1549–3544 relative to the Sun:  $d = 4$  pc at  $V_r = +50 \text{ km s}^{-1}$  (1),  $V_r = +25 \text{ km s}^{-1}$  (2),  $V_r = -50 \text{ km s}^{-1}$  (3), and  $V_r = -25 \text{ km s}^{-1}$  (4).

Table 1: Stars and multiple systems with trigonometric parallaxes

Star	$\alpha_{J2000},$ $\delta_{J2000}$	$\mu_\alpha, \text{ mas yr}^{-1}$ $\mu_\delta, \text{ mas yr}^{-1}$	$\pi, \text{ mas}$	$V_r, \text{ km s}^{-1}$	Ref*
GJ 65 AB	$1^h39^m01^s.54$ $-17^\circ57'01''.8$	$3296 \pm 5$ $563 \pm 5$	$373.7 \pm 2.7$	$29.0 \pm 4.6$	e
GJ 299	$8^h11^m57^s.58$ $8^\circ46'22''.1$	$1099 \pm 8$ $-5123 \pm 8$	$146.3 \pm 3.1$	$-35 \pm 5$	e
GJ 388 AB	$10^h19^m36^s.28$ $19^\circ52'12''.1$	$-502 \pm 8$ $-43 \pm 8$	$204.6 \pm 2.8$	$11.6 \pm 0.3$	e
GJ 406	$10^h56^m28^s.86$ $7^\circ00'52''.8$	$-3842 \pm 8$ $-2727 \pm 8$	$419.1 \pm 2.1$	$19.5 \pm 0.4$	a
GJ 473 AB	$12^h33^m17^s.38$ $8^\circ46'22''.1$	$-1730 \pm 8$ $203 \pm 8$	$227.9 \pm 4.6$	$0.9 \pm 1.7$	d
GJ 866 ABC	$22^h38^m33^s.73$ $-15^\circ17'57''.3$	$2314 \pm 5$ $2295 \pm 5$	$289.5 \pm 4.4$	$-50 \pm 1$	c
GJ 905	$23^h41^m54^s.99$ $44^\circ10'40''.8$	$111 \pm 8$ $-1584 \pm 8$	$316.0 \pm 1.1$	$-78.0 \pm 0.4$	a
GJ 1111	$8^h29^m49^s.35$ $26^\circ46'33''.7$	$-1112 \pm 5$ $-611 \pm 4$	$275.8 \pm 3.0$	$9.0 \pm 0.5$	b
GJ 3323	$5^h01^m57^s.47$ $-6^\circ56'45''.9$	$-550 \pm 5$ $-533 \pm 5$	$187.9 \pm 1.3$	$42.0 \pm 0.1$	b
GJ 3379	$6^h00^m03^s.50$ $2^\circ42'23''.67$	$311 \pm 3$ $-42 \pm 3$	$190.9 \pm 1.9$	$30.0 \pm 0.1$	b

Note. The radial velocities were taken from the following papers: (a) Nidever (2002), (b) Montes et al. (2001), (c) Delfosse et al. (1999), (d) Tinney and Reid (1998), (e) Barbier-Brossat and Figon (2000); the parallaxes are given according to the RECONS list of 100 nearest stars.

Table 2: Candidates for a close encounter with the Solar system

Star	SP	$M/M_{\odot}$	$d_{min}$ , pc	$t_{min}$ , thousand yr
GJ 905	M5.5V	0.12	$0.93 \pm 0.01$	$37.1 \pm 0.2$
GJ 3379	M3.5V	0.19	$1.32 \pm 0.03$	$-163 \pm 3$
GJ 65 AB	M5.5V/M6.0V	0.11/0.10	$2.21 \pm 0.12$	$-29 \pm 2$
GJ 406	M6.0V	0.09	$2.24 \pm 0.02$	$-15 \pm 1$
GJ 3323	M4.5V	0.15	$2.25 \pm 0.05$	$-104 \pm 3$
GJ 866 ABC	M5.0V/-/-	0.11/0.11/0.10	$2.52 \pm 0.07$	$32.3 \pm 0.3$

Table 3: Stars with spectroscopic or photometric distance estimates

Star	SP	$M/M_{\odot}$	$d_{min}$ , pc	$t_{min}$ , thousand yr	$V_r$ , km s <sup>-1</sup>	$P_1$
SSSPM J1549-3544	>DC11	$\approx 0.5$	$1.21 \pm 0.58$	$-72 \pm 6$	+50	0.09
SSSPM J1549-3544			$1.21 \pm 0.58$	$+72 \pm 6$	-50	0.09
SDSS J1416+1348	L5V	$\approx 0.08$	$1.24 \pm 0.65$	$186 \pm 44$	$-42.2 \pm 5.1$	0.05